Journal of Engineering and Development, Vol. 11, No. 1, March (2007) ISSN 1813-7822

Effect of High Elevated Temperatures on the Compressive Strength and Ultrasonic Pulse Velocity of High Strength Concrete

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Abstract

In this study, the effect of fire on the compressive strength of high strength concrete (HSC) is investigated. Two different tests, one of them is the non destructive test which is the ultrasonic pulse velocity (UPV) test and the other is the destructive compression test, are carried out using (10cm) cubes. Forty-five cubes (one third of them are of normal strength concrete (NSC) with original strength of (52.67 MPa) and the other two thirds are of (HSC) with original strength of (61.04 and 72.33 MPa), respectively, are heated to temperature levels of (200, 400, 600, and 800°C). Then after specimens are air cooled and (UPV) test is done, the specimens are destructively tested. The results indicated that, the residual compressive strength after high temperature exposure of the (NSC) is higher than that of (HSC),for example, the residual compressive strength after exposure to temperature level (800°C) for the former is (39.5%) while for the later is(19.5%) at worst case from their original strength. Also, the compressive strength reaches its peak value in the (NSC) earlier than the (HSC). Statistical analysis is made to find mathematical relationships to relate the results of the destructive test with that of non destructive test for both the (NSC) and (HSC), also to relate the results of (HSC) with that of (NSC).

الخلاصـــــــة

الدراسة الحالية تسلط الضوء على بحث تأثير الحرارة على مقاومة الانضغاط للخرسانة ذات المقاومة العالية.اجري نوعان من الفحوصات احدهما لااتلافي وهو فحص سرعة الأمواج فوق الصوتية (UPV) والأخر إتلافي باستعمال مكعبات طول ضلعها(١٠سم).تم تسخين(٤٥) نموذج (ثلثها بمقاومة انضغاط اعتيادية مقدارها(٥٢.٦٧)ميكا باسكال والثلثان الآخران بمقاومة انضغاط عالية مقدارها (٦١.٠٤ و٧٢.٣٣) ميكا باسكال على الترتيب إلى مستويات من درجات الحرارة هي(٢٠٠و٤٠٠و٦٠٠و٨٠٠)درجة سيليزية. فحصت النماذج لا أتلافيا بعد تبريدها بتعريضها للهواء ثم فحصت أتلافيا. بينت النتائج بان المقاومة المتبقية- بعد تعريض النماذج إلى الدرجات الحرارية المذكورة أعلاه- في النماذج ذات المقاومة الاعتيادية أعلى من تلك التي تمتلك مقاومة انضغاط عالية وكمثال على ذلك فان المقاومة المتبقية للأولى(٣٩.٥%)وللثانية (١٩.٥%) في أسوء الحالات من مقاومتها الأصلية بعد تعريض النماذج إلى (٨٠٠)درجة سيليزية بالإضافة إلى ذلك فان مقاومة الانضغاط للنماذج ذات المقاومة الاعتيادية تصل إلى قيمتها القصوى عند درجات حرارية اقل من تلك التي تصل فيها النماذج ذات مقاومة الانضغاط العالية. اجري تحليل إحصائي للنتائج لإيجاد علاقات رياضية تربط نتائج الفحوص الاتلافية بتلك غير الاتلافية للخرسانة الاعتيادية والعالية المقاومة، وكذلك لربط النتائج الخاصة بالخرسانة العالية المقاومة بتلك الاعتيادية.

1. Introduction

In recent years, the construction industry has shown significant interest in the use of high strength concrete (HSC). This is due to the improvements in structural performance, such as high strength and durability that it can provide compared to traditional normal strength concrete (NSC) [1]. In buildings, (HSC) structural members are designed to satisfy the requirements of the serviceability and safety limit states. One of the major safety requirements in building design is the provision of appropriate fire safety measures for structural members [2] in spite of the fact that, in general concrete has good properties with respect to fire resistance, since the period of time under fire after which concrete can continue to perform satisfactorily is relatively high [3]. The basis of this requirement can be attributed to the fact that, when other measures for containing the fire fail, structural integrity is the last line of defense [2]. To be able to predict the response of structures employing (HSC) during and after exposure to high temperature, it is essential that the strength of (HSC) subjected to high temperatures be clearly understood. In this work, an experimental program is directed to study the residual (HSC) concrete compressive strength after exposure to high temperatures up to (800°C), using concrete cube samples. Non destructive test (UPV) is taken to the same samples. Also, statistical analysis to the experimental results to predict the (HSC) concrete compressive strength mathematically is made. The aim of this work is to provide an understanding of the behavior of the (HSC) concrete when exposed to high temperatures.

2. Experimental Program

In the experimental work, forty-five concrete cubes of (10x10x10 cm) are used to carry out the non destructive test (UPV) and the destructive concrete compressive strength test.

A single concrete mix of (1:1.5:2) (cement: fine aggregate: coarse aggregate) in proportion by weight is used with two w/c ratios of (0.4) in proportion by weight for (NSC) specimens and (0.27) for that of (HSC). The cement content for the (NSC) is (492 kg/m^3) while for the (HSC) is (526 kg/m^3). The specimens are divided into three groups; each group consists of (15 cubes). Group A specimens are of (NSC) with original strength of (52.67 Map), while group B and C specimens are of (HSC) with original strengths of (61.04 and 72.33 MPa), respectively. The high strength is obtained, in addition to the reduced w/c ratio, by using a superplasticiser which is (Glenium 51) with different dosages. Group B strength is obtained by adding dosage of Glenium 51 of (1.5 liter per 100 kg of cement), while for group C the dosage is (1.0 liter per 100 kg of cement). The cubes are heated to four temperature levels of (200, 400, 600, and 800°C). Three cubes of each group are heated to each temperature level, and three cubes from each group are tested at room temperature as reference specimens.

Ordinary Portland cement (type I), which is manufactured in Kubaisa factofy according to Iraqi Standards (1QS 5:1984) is used. Fine aggregate from Rahhalia (Anbar) region, and crushed river gravel from (Al-Nibaa'ai) region with maximum size of (10 mm) are used.

After about (24 hours) from casting time, the specimens are stripped from their moulds, and placed in water containers to be cured for (28 days). Then after, the specimens are stripped out from the water containers, and left in the laboratory environment for (6 hours) to be dried then tests are carried out.

The heating process is carried out using electrical furnace. The specimens are heated slowly at a constant rate of (4 °C/min) to avoid steep thermal gradient [4]. Once the required temperature level is attained the specimens are saturated thermally at that level for one hour. The specimens are then air cooled until testing.

At the time of testing, non destructive test is taken to the specimens using the (UPV). The (UPV) test is made on three places two of them parallel to the direction of compacted layers (perpendicular to load application) and the other normal to it. After carrying out the non destructive test, the concrete compressive strength for each cube is tested (destructively).

3. Results and Discussions

3.1 Concrete Compressive Strength

The results of the experimental work are represented in **Fig.(1)** and **Fig.(2)**. **Figure (1)** shows the compressive strength-temperature relationship for the three groups of specimens, while the percentage residual compressive strength-temperature relationship is shown in **Fig.(2)**.

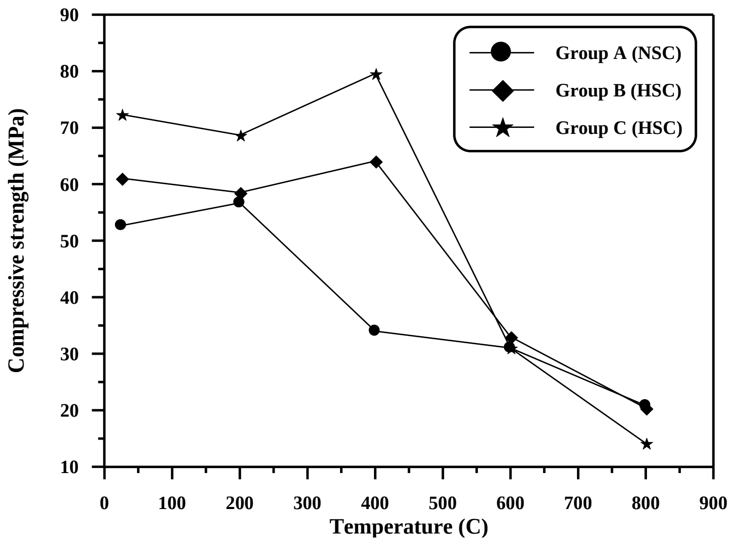

Figure (1) Compressive strength-temperature relationship for (HSC) and (NSC)

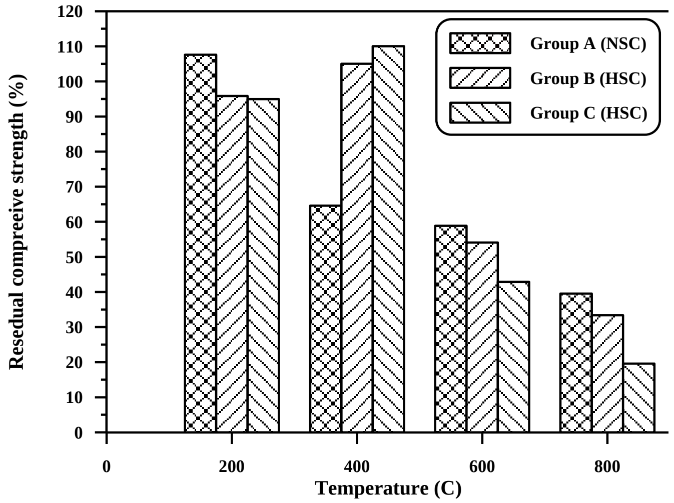

Figure (2) Residual compressive strength-temperature relationship for (NSC) and (HSC)

From the observation of the mentioned figures it can be noticed that:

- Concrete compressive strength for both (NSC) and (HSC), generally appears to follow a common trend by suffering a noticeable deterioration when exposed to high temperatures except at some regions which is discussed in the next points. This is an expected result, since exposing to elevated temperatures makes a lot of physical and chemical changes in concrete, such as loss of moisture, thermal movements between cement paste and aggregate, and dehydration of the calcium silicate hydrated in the cement paste [5,6]. These changes lead to the initiation of thermal microcracks and growth of the cracks that are formed previously either in the earlier stages of heating or cracks that exist before heating (drying shrinkage cracks), and consequently lead to deterioration of concrete strength.
- The compressive strength of (HSC) shows a reduction in lower temperatures (room temperature to 200°C) whiles for the (NSC) shows an increase in that range in the present study. It is expected that the compressive strength of the (NSC) may also be reduced at untested temperature between (room temperature and 200°C), because it is believed that absorbed water in concrete softens the cement gel or attenuates the surface forces between the particles (Van der Walls forces), thus reducing the strength in lower elevated temperatures [5]. Also, the reduction in lower temperatures may be attributed to the triaxial state of stress apparently existing when the paste pores are filled with water [7, 8].
- A little increase in strength for both (NSC) and (HSC) is associated with further increase in temperature. This increase may be attributed to the general stiffening of cement gel or the increase in surface forces between gel particles due to the removal of adsorbed water [9].
- The compressive strength of (NSC) begins to increase earlier than that of (HSC): since while the compressive strength of the (NSC) reaches its peak value at temperature level (200°C), the compressive strength of the (HSC) reaches its peak value at (400°C). As mentioned previously, the increase in strength is due to removal of adsorbed moisture. The temperature at which adsorbed water is removed and strength begins to increase

depends on the porosity of concrete [9]. The adsorbed moisture in (NSC) specimens escaped before that of (HSC) since the (HSC) is denser than the (NSC), the adsorbed water could not escape until after (200°C). Thus, the recovery of strength in (HSC) is delayed.

- The loss of strength resulting from exposure to high temperatures in (NSC) is smaller than the loss in (HSC). This difference is particularly noticeable in temperature levels after reaching to the peak value for the two i.e. after (400°C). The main reason concerns with the presence of adsorbed water at low temperatures. When concrete specimens are saturated with water, the water first fills the capillary pores and the remaining amount is adsorbed between the paste particles. In (HSC) which usually is also of high density and has fewer capillary voids, most of water is adsorbed causing a higher loss of compressive strength.

3.1.1 Effect of Original Strength

Figure (1) shows a comparison of concrete compressive strength temperature relationships for the three groups of specimens group A (NSC, 52.67MPa), group B (HSC, 61.04MPa), and (HSC, 72.33MPa), respectively. It is observed that the compressive strength-temperature relationship curve for the (HSC) differs from that of (NSC). This may lead to the conclusion that the original compressive strength has a noticeable effect on the residual compressive strength after heating.

This conclusion may be more clear and noticeable when **Figure (2)** is examined. **Figure (2)** shows a comparison of the percentages residual compressive strength-temperature relationship for the three groups. It is shown that the percentage of residual compressive strengths for the three groups of specimens have similar distribution in the all tested temperature levels except at temperature level (400°C) where the (HSC) specimens reaches its peak value. It can be noticed that, as the original compressive strength increases the residual compressive strength decreases. The percentage residual compressive strength for the (NSC) specimens are (107.59%, 64.55%, 58.86%, and 39.51%) at temperature levels (200, 400, 600, and 800°C), respectively. While for the (HSC) specimens group B the percentages are (95.84%, 105%, 54.06%, and 33.36%) and group C specimens have the same sequence as group B at the same previously mentioned temperature levels. These observations confirm the conclusion that the original strength (in the studied range) has a significant effect in the compressive strength behavior after high temperature exposure.

3.2 Ultrasonic Pulse Velocity (UPV)

The relation between (UPV) and temperature for the three studied groups of specimens are shown in **Figures (3, 4, 5 and 6)** in the direction parallel and perpendicular to the direction of compacted layers.

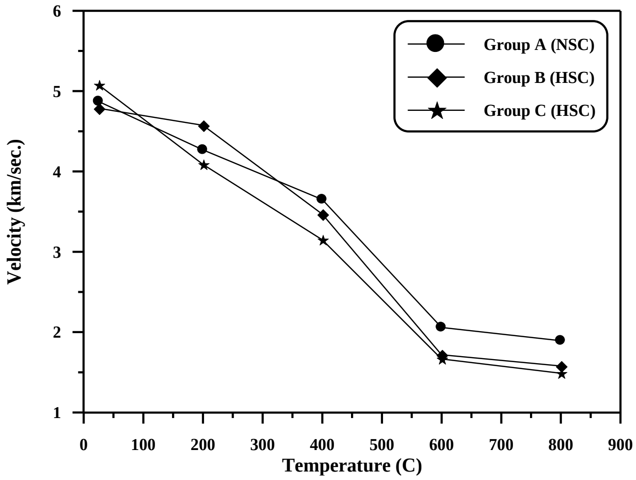

Figure (3) (UPV) parallel to the direction of compacted layers-temperature relationship for (NSC) and (HSC)

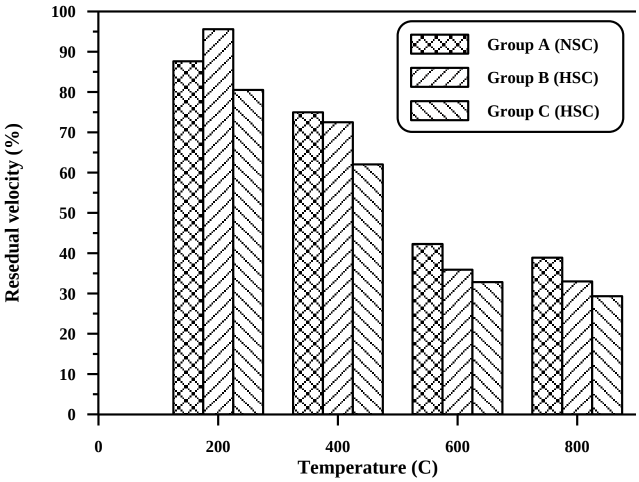

Figure (4) Residual (UPV) parallel to the direction of compacted layers-temperature relationship (NSC) and (HSC)

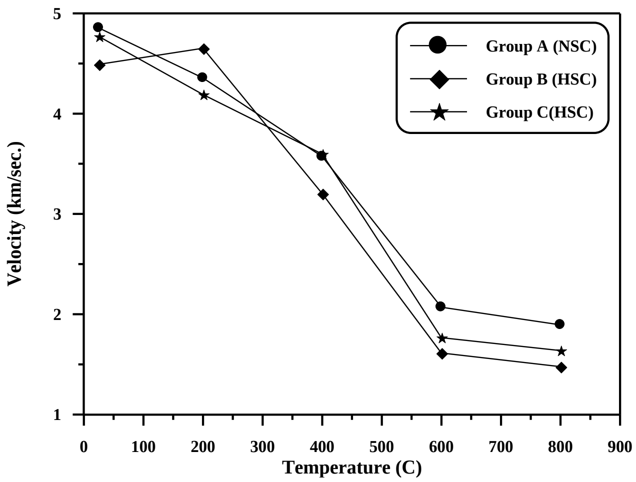

Figure (5) (UPV) perpendicular to the direction of compacted layers-temperature relationship for(NSC) and (HSC)

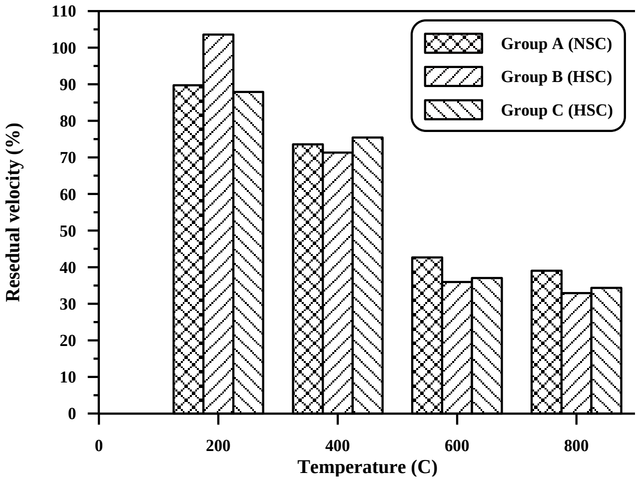

Figure (6) Residual (UPV) perpendicular to the direction of compacted layers-temperature relationship (NSC) and (HSC)

From the observation of the above **Figures (3, 4, 5 and 6)** it can be seen in general that the velocity shows decrease as the temperature increases, since the exposure of concrete to high temperature leads to the vaporization of moisture not bound by the hydrated compounds (free moisture) leaving voids behind in the concrete mass [5]. In addition, the heating process leads to fined cracks resulted from volume changes, which take place due to the thermal movements between cement paste and aggregate, which attributed to the differential thermal expansion between the cement past and aggregate. Also, the chemical and physical effects of the heating process at higher temperature (dehydration of calcium silicate at about 400°C) [10] leads also to volume changes which play the main role in the cracking and deterioration of concrete at higher temperatures. These voids retard the ultrasonic pulse leading to increase the travel time and consequently decrease the velocity.

3.2.1 (UPV) Parallel to the Direction of Compacted Layers

The results are shown in **Figures (3 and 4)**. The recorded velocities for group A, B and C before heating are (4.87,4.79 and 5.08 km/sec), respectively, while after heating to temperature levels (200, 400, 600,and 800°C) the (UPV) for group A are (4.27, 3.65, 2.06, and 1.89 km/sec.), respectively, for group B the (UPV) are (4.57, 3.47, 1.72, and 1.58 km/sec), respectively, and for group C are (4.09, 3.15, 1.67 and 1.49 km/sec), respectively at the same temperature levels mentioned for group A.

Figure (4) shows the percentage residual (UPV) at each tested temperature level. From this figure it can be seen that the percentage residual velocity loss is (12.4%) for (NSC) and (19.5%) for (HSC) at worst case after exposure to temperature level (200°C). The percentage loss is about (25.1%, 57.7% and 61.1%) for (NSC) and about (38%, 67.2%, and 70.7%) for (HSC) at worst case (which is occurred at group C) after exposure to temperature levels (400, 600, and 800°C).

3.2.1.1 Effect of Original Strength

From these results it can be noticed from **Figure (3)** generally that the (UPV) for the (HSC) is higher than or sometimes nearly equal to that of (NSC) before heating. As the temperature increase the velocities become lower for the (HSC) than that of (NSC) but in temperature level (200°C) group B has the highest value. From **Fig.(4)** it can be noticed that the percentage residual velocities for the (HSC) is lower than that of (NSC) and have the same distribution at all tested temperature levels higher than (200 °C) in which group B (HSC) has a highest percentage residual velocity but group A (NSC) still has higher value than group C (HSC).

3.2.2 (UPV) Perpendicular to the Direction of Compacted Layers

The results are shown in **Figures (5 and 6)** the recorded velocities for group A , B and C before heating are (4.85, 4.49 and 4.77 km/sec), while after heating to temperature levels (200, 400, 600, and 800°C) the (UPV) for group A are (4.35, 3.57, 2.07, and 1.9km/sec), while for group B are (4.65, 3.2, 1.61, and 1.48 km/sec) and for group C are (4.19, 3.6, 1.77, and 1.64 km/sec), respectively. **Figure (6)** shows the percentages residual velocities at each tested temperature levels for the three groups. From this figure it can be seen that the percentage residual velocity is (10.3%) for (NSC) and (12.1%) for (HSC) at worst case after exposure to temperature level (200°C). The percentage loss is about (26.4%, 57.4%, and 61%) for (NSC) and about (28.7%, 64.1%, and 67.1) for (HSC) at worst case (which is occurred at group B) after exposure to temperature levels (400, 600, and 800°C), respectively.

3.2.2.1. Effect of Original Strength

From the observation of these results, it can be seen that there is no clear conclusion can be recorded except that for higher temperature levels the velocities for group B and C (HSC) is lower than that of group A (NSC). From **Fig.(6)** it can be seen that the distribution of the percentage residual velocities in the tested temperature levels (200 and 400°C) is different while at temperature levels (600 and 800°C) is similar but different than that at (200 and 400°C).

4. Comparison between Residual (UPV) and Destructive Compressive Strength

The behavior of both concrete compressive strength and non destructive test (UPV) after exposure to high temperatures are shown in **Figs.(7, 8, and 9)**.

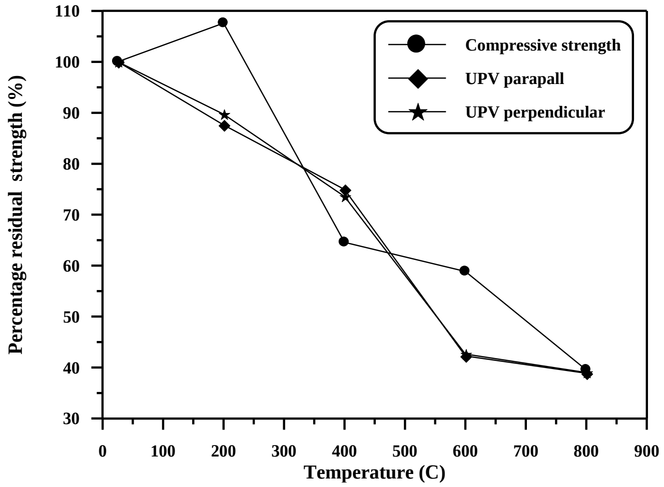

Figure (7) Residual compressive strength, and (UPV)-temperature relationship for (NSC) (group A)

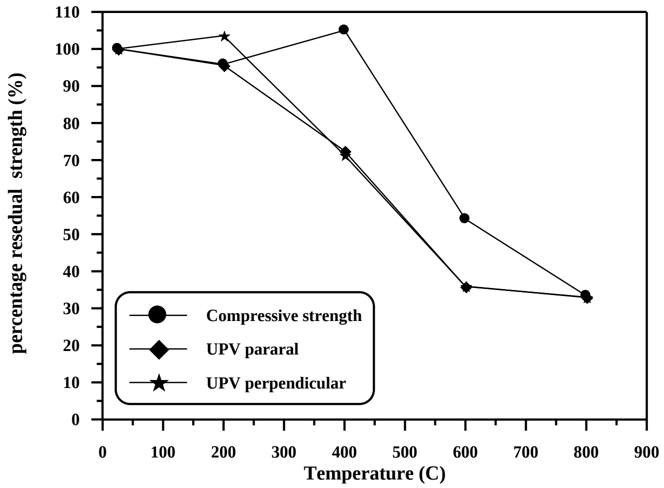

Figure (8) Residual compressive strength, and (UPV)-temperature relationship for (HSC) (group B)

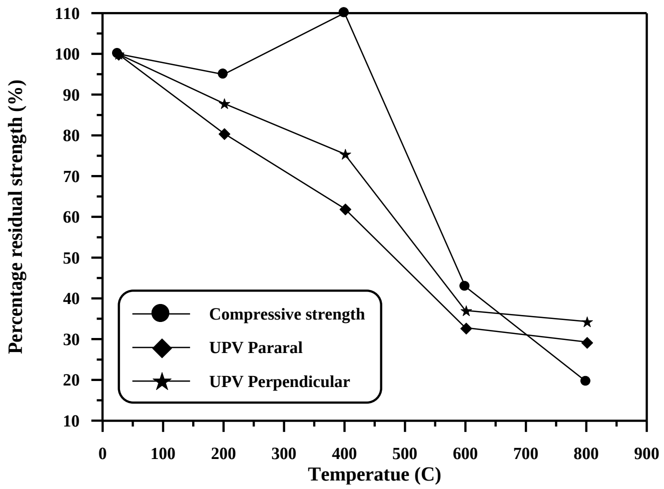

Figure (9) Residual compressive strength, and (UPV)-temperature relationship for (HSC) (group C)

When these figures are noticed a problem can be discussed, which is the shape of percentage residual strength-temperature relationship. **Figure (7)** shows the comparison between the residual compressive strength and the (UPV) in two directions parallel and perpendicular to the direction of the compacted layers for the (NSC). As shown in the figure, the percentage residual compressive strength displays two different behaviors. First, a rising line between room temperature and (200°C) is noticed, which reflects the rising in the compressive strength occurred at (200°C). Thereafter the specimens forming a decline line, which reflects the loss in strength, occurred. The percentage residual (UPV)-temperature relationship did not show similar behavior to that of concrete compressive strength. Where there is no any recovery at (200°C), instead, there is a continuous decrease as temperature increase. **Figures (7 and 8)** show the same comparison but for (HSC) group B and C, respectively. As shown in the figures, the percentage residual compressive strength displays three different behaviors. First decline line between room temperature and (200°C) then, a rising line to (400°C) and finally, a decline line after this temperature. Also as in the (NSC), the percentage residual (UPV)-temperature relation ship did not show similar behavior to that of compressive strength of (HSC). Where there is no strength recovery at (400°C) instead there is a continuous decrease as temperature increase except that increase in the residual (UPV) perpendicular to the direction of the compacted layers for group B specimens at temperature level (200°C).

5. Statistical Analysis

Statistical analysis are made using (SPSS) program (version 10) to find many relationships between the results obtained in the present experimental work to find some of them as a function of the others. These results are presented in **Table (1)** and the coefficients of correlation (R) and coefficients of determination (R^2) are also presented in the same table. Linear relationships are selected for simplicity and for its good correlation coefficients. From these equations, the compressive strength of (HSC) can be fond from the results of (NSC) for example by first finding the velocities of (HSC) from that of (NSC) and substitute them with the temperature level wanted in equation (4). The variables used in that Table mean:

t = temperature in (°C).

Fcu = compressive strength of (NSC) in (MPa).

Fcu_{hB} *= compressive strength of (HSC) group (B) concrete in (MPa).*

Fcu_{hC} *= compressive strength of (HSC) group (C) concrete in (MPa).*

V_p *= ultrasonic pulse velocity of (NSC) parallel to the compacted layers direction in (km/sec).*

V_{phB} *= ultrasonic pulse velocity of (HSC) group (B) parallel to the compacted layers direction in (km/sec).*

V_{phC} *= ultrasonic pulse velocity of (HSC) group (C) parallel to the compacted layers direction in (km/sec).*

V_n *= ultrasonic pulse velocity of (NSC) perpendicular to the compacted layers direction in (km/sec).*

V_{nhB} *= ultrasonic pulse velocity of (HSC) group (B) perpendicular to the compacted layers direction in (km/sec).*

V_{nhC} = ultrasonic pulse velocity of (HSC) group (C) perpendicular to the compacted layers direction (km/sec).

Table (1) Statistical relationships

	Variables	Equations	R%	R^2%
1	Fcu = f (t)	Fcu =57.696-0.0461(t)	93.8	88
2	Fcu_{hB} = f (t)	Fcu_{hB}=69.781-0.0553(t)	87.3	80.2
3	Fcu_{hC} = f (t)	Fcu_{hC}=85.421-0.0797(t)	85.4	82.8
4	Fcu = f (t, V_p, V_n)	Fcu=46.26-0.0353(t)-86.899(V_p)+88.985(V_n)	99.7	99.3
5	Fcu_{hB} = f (t,V_{phB},V_{nhB})	Fcu_{hB}=-3.026+0.01027(t)+40.655(V_{phB})-27.475(V_{nhB})	91.6	83.9
6	Fcu_{hC}= f (t,V_{phC},V_{nhC})	Fcu_{hC}=97.82-0.123(t)-81.242(V_{phC})+ 86.664(V_{nhC})	98.9	97.8
7	V_p = f (t, V_n)	V_p=-12.6+1.194×10^{-4}(t)+1.023(V_n)	99.9	99.8
8	V_{phB} = f (t, V_{nhB})	V_{phB}=1.111-9.74×10^{-4}(t)+0.812(V_{nhB})	99.7	99.4
9	Fcu_{hB} = f (t, Fcu)	Fcu_{hB}=102.668-0.0815(t)-0.57(Fcu)	88.6	78.5
10	Fcu_{hC} = f (t, Fcu)	Fcu_{hC}=141.048-0.124(t)-0.964(Fcu)	87.1	80
11	V_{phB} = f (t, V_p)	V_{phB}=-0.911+2.702×10^{-4}(t)+1.203(V_p)	99.3	98.6
12	V_{phC} = f (t, V_p)	V_{phC}=0.934-1.47×10^{-3}(t)+0.823($V_{p)}$	99.4	98.8
13	V_{nhB} = f (t, V_n)	V_{nhC}=-2.013+1.15610^{-3}(t)+1.383(V_n)	98.5	97.1
14	V_{nhC} = f (t, V_n)	V_{nhC}=1.236-7.31×10^{-4}(t)+1.233(V_n)	99.8	99.6

6. Conclusions

1. The compressive strength-temperature relationship for the (NSC) differs from that of (HSC) in the tested temperature levels in the present study. The strength of the (NSC) increases at (200°C), then it suffers a continuous decrease at all the other tested temperature levels; while the strength of the (HSC) suffers a reduction at temperature level (200°C) after that it increases at temperature level (400°C) then it decreases continuously at the remaining temperature levels (600 and 800°C).
2. The (NSC) reach its peak value at temperature level (200°C), which is higher than its original strength by (7.5%) from its original strength, while the (HSC) reaches its peak value at temperature level (400°C) which is higher than its original strength in the range of (5-10%) from its original strength.
3. The loss in strength resulting from exposure to high temperature in (NSC) is smaller than that in (HSC) except at temperature level (400°C) where the (HSC) reaches its peak value. The loss in strength after exposure to (800°C) for the (NSC) (60.5%), while for the (HSC) is in the range of (66.6-80.4%) from its original strength.

4. The (UPV) parallel to the direction of compacted layers of (HSC) is lower than that of (NSC) after exposure to high temperatures. Also, the percentage residual velocities of the (HSC) are lower than that of (NSC). The percentage residual velocities for the (NSC) after exposure to temperature level (800°C) (38.9%), while for the (HSC) is in the range of (33-29.3%) from their original velocities.
5. The original strength is insignificant in the (UPV) behavior in the direction perpendicular to the direction of the compacted layers.
6. The percentage residual (UPV)-temperature relationship did not show similar behavior to that of compressive strength of (HSC) where there is no strength recovery at (400°C) instead there is a continuous decrease as temperature increases.

7. References

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